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Residual Soil Nitrogen Scenario Analysis of Canadian Farmland using a Canadian Agricultural Nitrogen Budget (CANB v4.0) Model

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Abstract: A Canadian Agricultural Nitrogen Budget (CANB) model has been developed since 2002 to estimate Residual Soil Nitrogen (RSN) and N leaching loss across Canadian farmland. The current results showed that national RSN averages in Canadian farmland (annual N input minus annual N output) increased from 9.4 kg N ha⁻¹ in 1981 to 23.6 kg N ha⁻¹ in 2011 as mainly affected by the increase in synthetic fertilizer N usage and biological N₂ fixation. With annual drainage, about 50 and 80% of residual soil N was lost in Central (Ontario and Quebec) and Atlantic Canada, respectively, through leaching and varying according to soil and climate conditions. The objective of this paper was to present nitrogen leaching scenario analysis using the CANBv4-scenario model. Agricultural regions (6 to 11) in each province were integrated with the CANBv4-scenario model to assess how RSN and N leaching losses change in response to nitrogen input scenarios in the studied agricultural region, province and ecoregion. Four scenarios were generated each with four levels: (1) reducing synthesized fertilizer N by 10 to 40%; (2) reducing manure N by 10 to 40%, (3) reducing N₂ fixation by 10 to 40% which was done by decreasing alfalfa land area by 10 to 40% while increasing improved pasture by that same land area and (4) combining scenarios 1, 2 and 3. The results showed that both residual soil N and N leaching loss decreased significantly with the reducing levels of synthetic fertilizer N, manure N, and N₂ fixation. Scenario 4 showed combined results of soil N leaching loss efficiently. For instance, soil N leaching loss could be reduced by 42% under a 20% reduction level in the three N sources in 2011 farmland practice. More results at provincial and regional scales were presented.

Keywords: Canadian Agricultural Nitrogen Budget (CANB) v4.0 model; Residual Soil Nitrogen; Nitrogen leaching loss; Scenario analysis; Soil Landscapes of Canada

1 INTRODUCTION

Agricultural production provides basic human food and fiber but it can also cause potential side effects to our environment if it is not properly managed. For example, nitrogen (N) provides essential nutrients for all plants and animals but inputting additional N to farmland can result in increased N losses to the air via greenhouse gases (N₂O, NO, N₂) (Rochette et al., 2008) and ammonia (NH₃) emissions (Sheppard et al., 2010) as well as to water via nitrate (NO₃) leaching and runoff (De Jong et al., 2009). Nitrogen cycle models in agricultural systems have been made by scientists or policy makers for decades to aim at monitoring the impact of nutrient cycling in agro-ecosystems to environmental quality. There is an

increasing trend for applying environmental modelling software/approach as a tool to assess environmental health (Buczko et al., 2010).

In Canada, an agri-environmental indicator report program was initiated in the last 20 years: indicator report series have been reported every 5 years since 2000 to outline the trend of changes of farmland management to soil, water and air quality (Drury et al., 2007; Eilers et al., 2010). A Canadian Agricultural Nitrogen Budget model (CANB) has been developed to estimate the annual nitrogen cycle (N input, N uptake, N losses from gases and nitrate leaching) at the regional Soil Landscapes of Canada scale (1:1M map) (Yang et al., 2007; 2013). The CANB v4.0 model was used to report changes of both Residual Soil Nitrogen (RSN) and the Indicator of Risk of Water Contamination by Nitrogen (IROWC-N) from 1981 to 2011 in the indicator report series #4. RSN is estimated as the difference between N inputs and N outputs as illustrated in equation (1). N inputs included N additions to farmland from inorganic fertilizer, manure, nitrogen fixation, atmospheric N deposition, mineralization of organic manure and crop residue. N outputs included N removal from soil by crop uptakes and N losses from greenhouse gas (N₂O, NO, N₂) emissions and ammonia (NH₃) gas emissions. Therefore, the RSN indicator provided an estimation of surplus N remaining in the soil after harvest. It directly related N use efficiency by annual crop production to N losses by leaching and runoff during long non-growing seasons (from harvest to spring). The IROWC-N indicator is the linked estimation of RSN losses through leaching immediately after harvest and the subsequent climate conditions during non-growing seasons (De Jong et al., 2009) using a semi-dynamic soil water balance model (De Jong et al., 2009). The CANB v4.0 model's structure and preliminary results were shown in previous publications (Yang et al., 2014). In this paper, a CANBv4-scenario model is presented to illustrate how RSN and N leaching loss changed in response to N input scenarios. The CANBv4-scenario model's outputs will be scaled up to various eco-regions, agricultural regions as well as provincial and national scales. The impact of changing N input scenarios to RSN and IROWC-N indicators will be discussed.

2 MODEL

The CANB model (written in Intel Fortran) (Figure 1) is designed at Soil Landscapes of Canada (SLC) v3.2 polygon scales (1:1M) (Soil Landscapes of Canada Working Group, 2005). The agricultural production, soil and land use databases were used in accordance with other data and rate parameters as input to the model. Two agro-environmental indicators were calculated annually and the main equations are shown below.

2.1 RSN module

The agricultural polygon numbers changed from 3247 to 3345 during a 31 year period (1981 to 2011). At each SLC, the RSN budget is estimated by the key equation below:

$$RSN = (N_{input} - N_{output}) / FarmlandA \quad (1)$$

Where RSN , N_{input} and N_{output} are in kg N ha⁻¹, $FarmlandA$ represents the total hectares of farmland area in each of the 3247 to 3345 soil polygons from 1981 to 2011.

N_{input} and N_{output} were calculated as:

$$N_{input} = N_{fertiliser} + N_{manure} + N_{man_min} + N_{fixation} + N_{fix_min} + N_{deposition} \quad (2)$$

$$N_{output} = N_{crop_removal} + N_{gas_N2O} + N_{gas_NH3} \quad (3)$$

where $N_{fertiliser}$ is the total synthetic fertilizer N applied to crops (kg N SLC^{-1}); N_{manure} is the amount of available inorganic N from manure applied to crops and pasture (kg N SLC^{-1}) after N losses; N_{man_min} is the amount of N mineralized from the organic manure that was applied in the 3 previous years; $N_{fixation}$ is the amount of N fixed by leguminous crops (kg N SLC^{-1}) after subtracting legume residue N being carried over to the next year; N_{fix_min} is the amount of N mineralized from legume residue and roots remaining from the 3 previous years; $N_{deposition}$ is the amount of wet and dry deposition of atmospheric N; $N_{crop_removal}$ is the amount of N removed in the harvested portion of crops and pasture (kg N SLC^{-1}), N_{gas_N2O} is the quantity of greenhouse gas (N_2O , NO and N_2) emissions to the atmosphere mainly via denitrification and N_{gas_NH3} is the amount of ammonia gas emissions to the atmosphere mainly via volatilization. Calculations for each N component listed in the (2) and (3) are given in previous papers (Yang et al., 2007; De Jong et al., 2009; Yang et al., 2011; 2013).

2.2 N leaching model

The nitrogen leaching model in CANB v4.0 was a simplified version of a daily IROWC-N model (De Jong et al., 2009) that was designed to calculate N leaching loss and N concentration in the leached water based on salt leaching concepts (Burns, 1974). The IROWC-N model takes RSN from the CANB model as input, then, the amount of N leaching from the soil into the drainage water during the non-growing season $N_{lostNGS}$ and growing season N_{lostGS} (kg N ha^{-1}) was estimated based on methods provided by De Jong et al (2009).

N concentration in the non-growing season ($N_{concNGS}$) (mg N L^{-1}) and the growing season (N_{concGS}) (mg N L^{-1}) was then calculated using the cumulative drainage water volumes in the growing (D_{GS}) and non-growing seasons (D_{NGS}). The drainage water of D_{GS} and D_{NGS} was estimated using a modified daily Versatile Soil Moisture Budget model which was integrated into the IROWC-N module using daily weather datasets across Canadian farmland (DeJong et al., 2009, Baier et al., 1979). Annual N lost is the sum of N lost in the two seasons as shown in (4). Annual N concentrations are calculated by using the drainage weighted averages of the N concentrations in the two seasons as displayed in (5).

$$N_{lostYR} = N_{lostGS} + N_{lostNGS} \quad (4)$$

$$N_{concYR} = (N_{concGS} \times D_{GS} + N_{concNGS} \times D_{NGS}) / (D_{GS} + D_{NGS}) \quad (5)$$

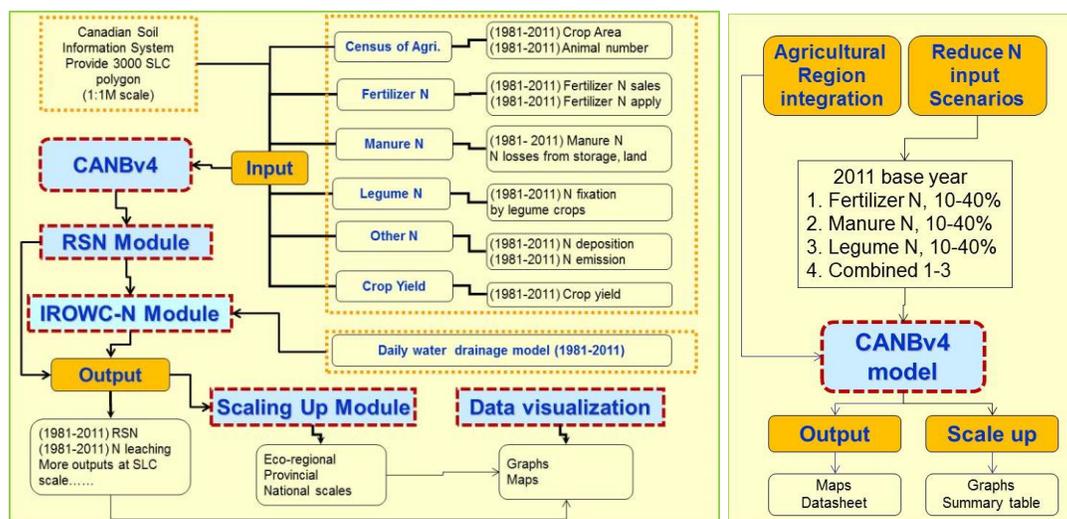


Figure 1: Flow chart of the Canadian Agricultural Nitrogen Budget (CANB) v4.0 model and integrated scenario analysis.

2.3 Input data collection

The model input datasets were collected from various sources based on different scales. The basic crop production dataset was obtained by integrating the Census of agriculture datasets to the SLC v3.2 database by the AAFC data working group (Soil Landscapes of Canada Working Group, 2005). The missing values were estimated and the datasets were linearly interpolated from census data gathered every 5 years (i.e., 1981, 1986, ..., 2011) to an annual dataset. In each polygon, the CANB v4.0 model used a total of 27 crop types (area, yield) and 21 livestock types (animal numbers) that were taken from the Census of Agriculture database. Crop area, yield, and livestock numbers are provided at the SLC scale as the basic agricultural production dataset to support the modelling work.

In addition to agricultural databases, N rate parameters were collected at various scales. The main rate parameters include fertilizer N recommendation rates that were established in 2001 farm managements at soil type. N concentrations in grain and dry biomass were collected at the Canada scale based on the latest Canadian Fertilizer Industry reports (CFI, 2006). Animal N excretion rates were collected from the ASABE 2006 standard at Canada scale. Nitrogen fixation rate parameters were collected at national scale from various publications.

The CANB v4.0 model estimated annual organic N from manure and legume residual carryover to the following year as well as it estimated annual N leaching loss at growing season (May to October), and non-growing season (November to April). For this reason, RSN and N lost should be calculated annually because the annual databases and parameters are required to support the model. Annual interpolations of crop area and animal number datasets were made at SLC scale since these datasets were reported every 5 years. Therefore, we have interpolated the annual datasets using two 5 year census data reports. For instance, crop area and animal numbers from 1982 to 1985 and 1987 to 1990 were interpolated based on datasets from 1981 and 1986, and 1986 and 1991 respectively. This method provided two annual datasets, crop area and animal number, from 1981 to 2011. Manure N management datasets were collected every 5 years at provincial scale. This data was also interpolated annually based on similar methods to those used for crop area. Data with respect to crop yield and fertilizer N sales was collected every year.

2.4 Output and scale up

The CANB v4.0 model estimated RSN and N components as shown in (1), (2) and (3) as well as N lost and N concentrations at SLC scale as shown in (4) and (5). The SLC outputs are scaled up to regional (Ecodistrict, Ecoregion and Ecozone), agricultural regional, provincial, and national scales. RSN and N components were mapped using 5 categories (very low, low, moderate, high and very high).

3 SCENARIO ANALYSIS

Canadian farmland is divided into 6 to 11 agricultural regions in western and central provinces, including British Columbia (BC), Alberta (AB), Saskatchewan (SK), Manitoba (MB), Ontario (ON) and Quebec (QC). The agricultural regions were integrated to the CANB v4.0 model so that the effects of RSN and IROWC-N changes to land management inputs can be analyzed from agricultural regions and other scales. The scenario analysis was carried out under 2011 business as usual practices (baseline). In this presentation, four scenarios were developed each having four levels. (1) reduction of fertilizer N by 10, 20, 30 and 40%; (2) reduction of manure N by 10, 20, 30 and 40%, (3) reduction of N₂ fixation by 10, 20, 30 and 40%, i.e. by decreasing alfalfa land acreages by 10, 20, 30 and 40% while increasing improved pasture by the same land area, respectively, and (4) combined scenarios from 1, 2 and 3. A total of sixteen scenarios were carried out by the CANBv4-scenario model and each output was compared with the 2011 baseline. RSN, N component and IROWC-N at SLC scale can be mapped by 5 classes; the scale up outputs can be analyzed by graphs or reports.

4 RESULTS AND DISCUSSION

4.1 Spatial and temporal changes

The results showed a significant increase of average RSN values: 9.4 kg N ha⁻¹ in 1981 to 23.6 kg N ha⁻¹ in 2011. Regional variation of RSN can be seen clearly. In 1981, the majority of farmland area in Western Canada was in both very low and low RSN classes, but some farmland area was found to be in high and very high RSN classes in southern Ontario and Quebec. In 2011, there had been a considerable shift of farmland area towards the medium and high classes in Western Canada and most farmland area fell into both high and very high classes in Central and Eastern Canada. The increase of RSN was mainly caused by the increase of fertilizer N and legume crop acreages (biological N₂ fixation).

Fertilizer N increased from 0.938 Tg (Tg = 10¹² g) in 1981 to 2.009 Tg in 2011 in Canadian farmland. In Western Canada, fertilizer N application rates changed from very low and low classes in most farmland area in 1981 (Figure 2a) to medium to high fertilizer N application classes in 2011 (Figure 2b). In Eastern Canada, fertilizer N application rates were in medium to very high classes in southwestern Ontario and southern Quebec in 1981 (Figure 3a), however more than 60% of farmland area fell into high and very high classes of fertilizer N in southern Ontario and Quebec in 2011 (Figure 3b).

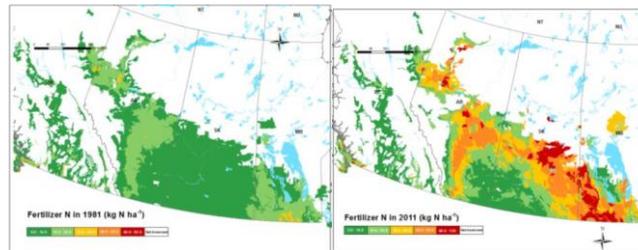


Figure 2. Fertilizer N application in western Canada in 1981 and 2011

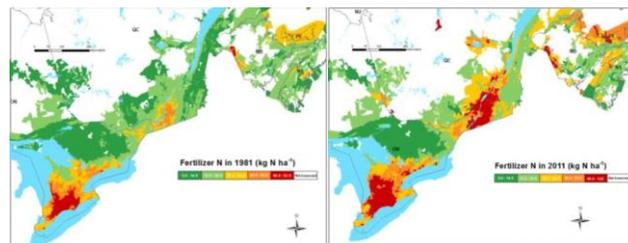


Figure 3. Fertilizer N application in Eastern Canada in 1981 to 2011

Similarly, biological N₂ fixation changed from 0.966 Tg in 1981 to 1.665 Tg in 2011 in Canadian farmland due to increased legume crop acreages. Although, manure N application has not significantly changed from 0.928 Tg in 1981, to the peak of 1.100 Tg in 2006, it then decreased to 0.911 Tg in 2011. N deposition from the air was small compared with N input from fertilizer, manure and N₂ fixation. Therefore, the increase of residual soil nitrogen was mainly driven by the increase of fertilizer N application and biological N₂ fixation.

4.2 Provincial changes

Provincial RSN and N leaching lost averages were low in Western Canada (Figure 4). On average, RSN values were between 20-30 kg N ha⁻¹ in British Columbia and 38% of annual RSN was leached in BC

(Figure 4). RSN values varied from 5-40 kg N ha⁻¹ in the prairies of Canada (AB, SK and MB) while only 3-14% of annual RSN was lost by leaching in these provinces due to semi-arid climatic condition (i.e., annual precipitations ranged 250-400mm) (Figure 4). On the other hand, average RSN values were high (i.e., 45-75 kg N ha⁻¹) in Eastern Canada (ON, QC, NB, NS and NL) and 33-90% of annual RSN was lost by leaching due to high precipitation (i.e. 600-1300 mm annually) (Figure 4).

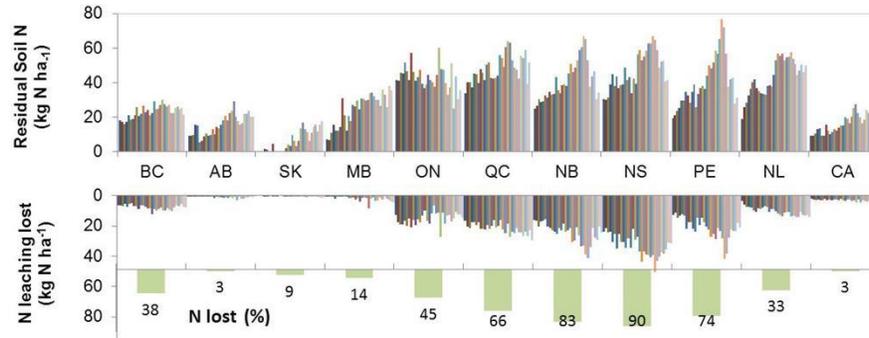


Figure 4. Provincial averages of RSN and N lost from 1981 to 2011

National RSN averages increased from 14 to 24 kg N ha⁻¹ from 1981 to 2011. These were affected by the significant increase in both fertilizer N and biological N₂ fixation (Figure 5).

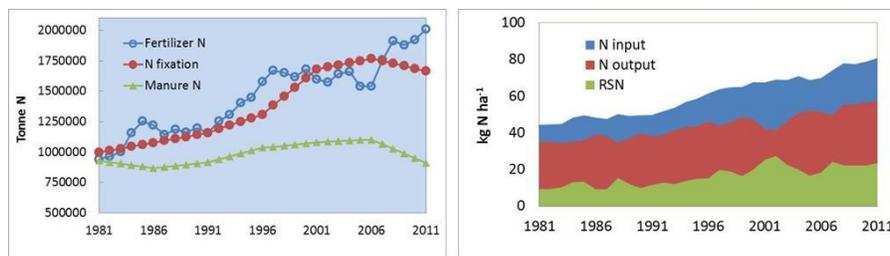


Figure 5. National N inputs (fertilizer N, N₂ fixation and manure N), N input, N output and RSN

4.3 Scenario results

Under scenario 4, average RSN values decreased linearly from 23.6 kg N ha⁻¹ at the 2011 baseline to 18.5, 13.6, 9.0 and 5.2 kg N ha⁻¹ under 10, 20, 30 and 40% reductions of fertilizer N (Figure 6a), manure N (Figure 6b) and biological N₂ fixation (Figure 6c) simultaneously. Additionally, average RSN values each decreased linearly in the studied agricultural regions, but they also showed significant differences among these regions in each province (Figure 7).

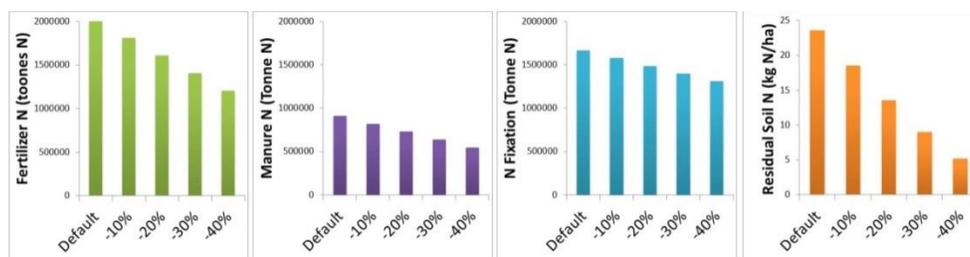


Figure 6. Average reduction of the three N inputs and the RSN values under scenario 4

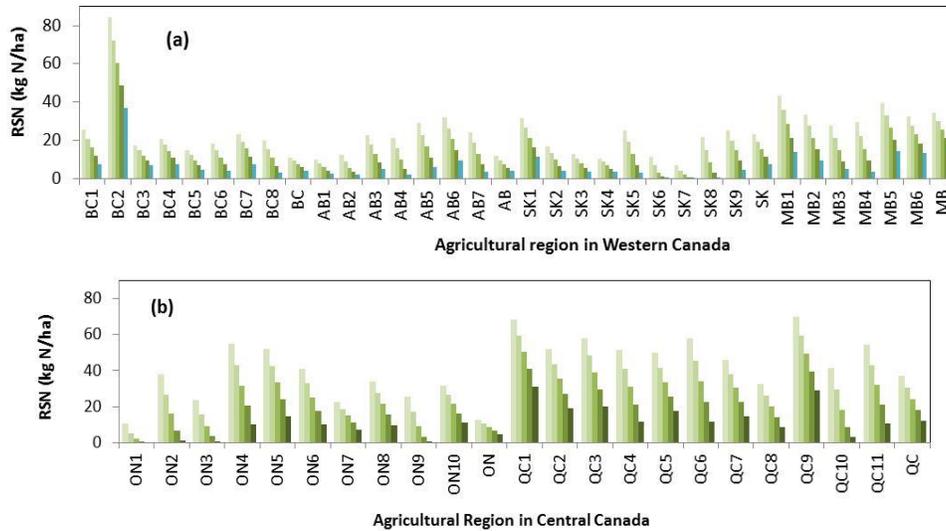


Figure 7. Average RSN in agricultural regions under scenario 4: (a) Western Canada, (b) Central Canada

An RSN level under SLC scale was mapped using RSN data from scenario 4-level 2 (reducing 20% of fertilizer N, manure N and biological N_2 fixation) (Figure 8). RSN and N lost were reduced by one risk class. National RSN decreased from 23.6 in the 2011 baseline to 13.6 $kg\ N\ ha^{-1}$ under a 20% combined reduction of the three N sources. RSN values were reduced by 42% which is similar to the RSN level in 1994.

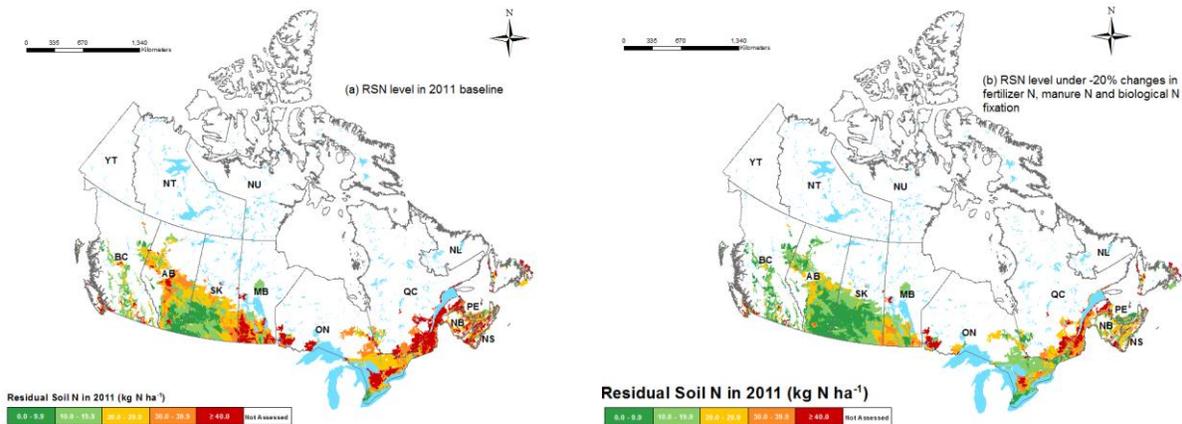


Figure 8. Residual Soil Nitrogen (RSN) levels on Canadian farmland in 2011 baseline (a), and a 20% reduction of fertilizer N, manure N and biological N_2 fixation under scenario 4 (b).

5 SUMMARY

RSN and N loss through leaching were successfully simulated by the Canadian Agricultural Nitrogen Budget model covering the 31 year period from 1981 to 2011 for Canadian farmland at the Soil Landscapes of Canada 1:1 million scale. Regional and temporal differences were significant due to the differences in N inputs and N outputs as well as diversified climate conditions across Canada.

A CANBv4-scenario model indicated that increased RSN values were mainly due to the continuous increase of N input from fertilizer and biological N_2 fixation compared to the moderate increase in N uptake by crop yields. Farm management response options should be established to reduce nitrate N leaching in

higher risk regions such as reducing fertilizer N application, controlling legume acreages as well as controlling livestock numbers in areas high in RSN of the agricultural regions.

The principle of the CANB v4.0 program can be applicable to other regional scales such as watershed, forestry or urban areas for estimating the surplus N that enters into the agro-ecosystem or the human food chain.

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